DUV ArF Light Source Automated Gas Optimization for Enhanced Repeatability and Availability

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ABSTRACT

The need for repeatable, reliable, and faster DUV ArF light source gas optimizations drove the development of Automated Gas Optimization (AGO). These automate the manual gas optimization procedure previously used to select the laser chamber gas pressures and in addition, bandwidth actuation settings, to deliver consistent performance and long gas lives, while maintaining stability and bounds on laser inputs. Manual gas optimization procedure requires at least two refills and an on-site visit by service personnel that can take over an hour to complete. This results in inconsistent light source performance, and sometimes unscheduled downtime. The key to AGO technology is the real-time estimation and monitoring of the laser's gas and bandwidth states, and automatic adjustment of gas pressure and bandwidth actuators until the states reach their specified targets, thus creating a closed loop. AGO executes on every refill, typically complete in less than 5 minutes, and collect performance data to allow long-term trending. They include built-in safety features and flexibility to allow future upgrades of light source features or performance tuning. Deployed in many lasers in the field, AGO has proved to be a dependable automation, yielding repeatable, fast, and reliable optimizations and valuable long-term trending data used to assess chamber performance

Keywords: DUV, Gas Optimization

1. INTRODUCTION

Cymer XLR light sources [1] have been serving the lithography industry for several years with steady improvement in its abilities through innovation in technology. Current generation lasers use Master Oscillator (MO) and Power Ring Amplifier (PRA) in a series configuration to generate pulsed laser light [2]. The chambers that house the laser cavity are filled with a mixture of gases under pressure that generate excimer laser light when pulsed with a pair of high voltage electrodes. Efficiency of a laser typically drops as more pulses are generated that is called chamber aging. In order to extend the useful life of the chamber, the losses are compensated by refilling the MO and PRA chambers with fresh gas mixture that helps remove contaminants that accumulate. Cymer's GLX technology [3] allows XLR lasers to generate 2 billion pulses before requiring a fresh gas refill. These refills are performed automatically by the laser. Every subsequent refill provides a diminishing marginal utility in terms of the available energy range the laser can produce. Traditionally, this loss has been compensated by changing the chamber gas pressure after several billion pulses. Increasing the gas pressure increases overall efficiency of the laser. However, too high of a pressure can deteriorate laser performance elsewhere as dictated by the highly coupled dynamics of the laser (see section 1.5). Therefore an optimization needs to be performed to find a suitable pressure. Since the introduction of fast spectral bandwidth (or simply "bandwidth") control technology in Cymer XLR lasers [4], another optimization parameter is coupled into the problem. A coarse bandwidth actuator (CBA) provides long range control over the bandwidth of laser light output at the cost of inaccurate control and actuation speed. This actuator does not move under normal laser operation but its position is critical in preventing the fast bandwidth actuator (FBA) from saturating while regulating the bandwidth to its target set point. Since pressure has a significant effect on the bandwidth and the fast control range, both pressure and the CBA position need to be optimized simultaneously during a gas optimization. Traditionally, the optimizations have been performed manually, and can require approximately 1 hour to complete during which laser cannot be used for production.

This article presents the enhanced Automated Gas Optimization (AGO) technology, which is an automated version of the manual optimization procedure that overcomes some of the limitations of the manual procedure and provides additional benefits. An automated version was previously demonstrated to work on systems without any bandwidth actuator optimization [5]. The enhanced version incorporates both pressure and bandwidth optimization.

1.1 Laser Overview

Figure 1 highlights the key components of the laser relevant to this article. This includes MO chamber, PRA chamber, CBA, FBA and high voltage supply source. The relevant physical quantities of interest are MO Energy, High Voltage (V), coarse bandwidth state (S) and fast bandwidth state (B) and PRA pressure (P). A dual voltage source excites the gas in the MO and PRA chambers in a pulsed fashion. A seed laser light is generated in the MO chamber which is amplified by the PRA chamber after a delay. Energy output from the MO and total system output energy are measured for each pulse. CBA is tuned so that bandwidth is near target when FBA is at its nominal position. During normal operation FBA keeps a tight control on the bandwidth. However the range of FBA is limited and sensitive to the position of CBA.

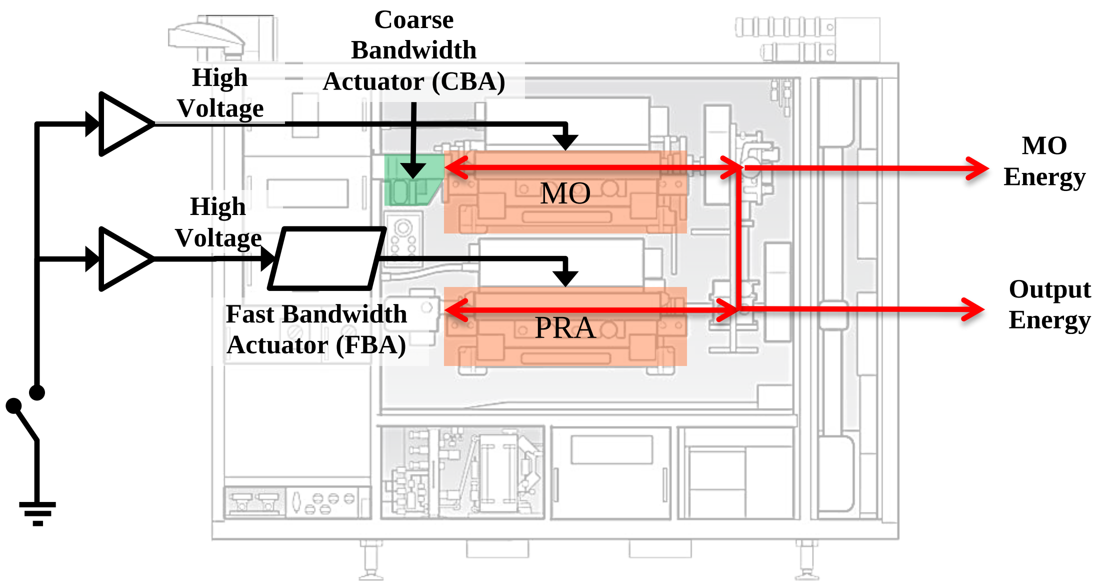

Figure 1 An XLR laser frame highlighting MO and PRA chambers that generate light. Coarse and fast bandwidth actuators control the bandwidth of the light

1.2 Automated Gas Optimization

1.3 Goals

The primary purpose of gas optimization is to set the gas pressure in MO and PRA chambers and adjust the CBA such that the laser can meet its specifications for the next several billion pulses. An optimization is always performed as an integral part of a gas refill. A gas refill resets the gas state of the MO and PRA chambers by flushing the chambers with fresh gas mixture at their respective maximum pressures. Subsequently the pressure is reduced in steps until an optimum condition is reached. During the procedure, the laser is pulsed to monitor performance and make any necessary adjustments. The enhanced AGO also performs adjustments to the CBA during this period for simultaneous pressure and bandwidth optimization.

A primary goal of the enhanced AGO is to completely replace the manual procedure with an automated procedure that could be executed with every gas refill optimizing laser's performance and its availability. Furthermore, opportunities were explored to make the procedure robust to variation in chamber dynamics. Determining whether a laser is capable of meeting all of its specifications is a difficult task. Nonetheless, a reasonable metric is expressed in terms of available margin to control the system output. Large margin implies that the actuators can compensate for larger disturbances. Therefore, the goal of optimization can be interpreted as the room available in bandwidth and energy control about their nominal set points. However measuring these quantities under all conditions remains a challenge and therefore the optimization is performed in absence of a formal cost function.

1.4 Constraints

Since one of the goals is to avoid any impact on the availability, it was determined that an automated gas optimization procedure that may be executed every 1 billion pulses along with a refill shall take no longer than 5 minutes. This was

computed based on the typical refill frequency, frequency of manual optimizations and the time required for manual optimization. The optimization procedure is limited to pressure changes that are negative, i.e., pressure can only be dropped and not increased. This constraint is to reduce the time consumed due to the slow process of increasing pressure while maintaining fluorine concentration. A refill initially increases the pressure to a maximum and from there it can be dropped in steps while monitoring system response. The optimal setting should correspond to a stable laser state which is defined by the amount of MO energy being produced for a nominal system energy output and the voltage required for generating the given nominal energy. If MO energy is too low then it will lead to poor measurements and overall increased likelihood of off-nominal pulses. Voltage should also be within a reasonable range to allow enough room for energy modulation about the nominal setting. Voltage and MO energy are readily measured and therefore can be used for determining when to stop the optimization. This procedure has was followed by the manual procedure before the AGO technology was introduced.

1.5 Open Loop Dynamics

As the laser fires more pules, chamber components wear out leading to loss in efficiency. This loss is compensated by increasing the pressure. Figure 2 illustrates this effect.

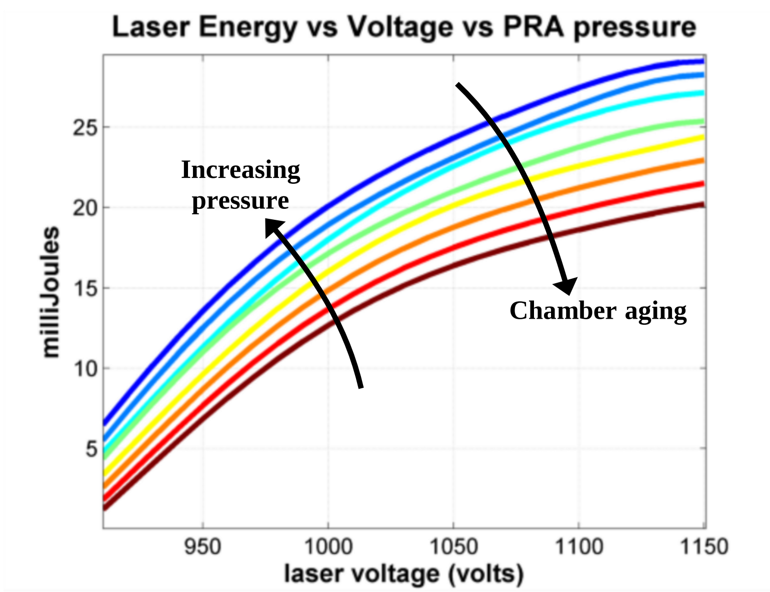

Figure 2 Chamber aging causes loss in efficiency that can be compensated by increasing the pressure

However, the laser dynamics are highly coupled, which constrains the amount of pressure that can be changed without deteriorating laser performance. The overall system can be represented in block structure as in Figure 3.

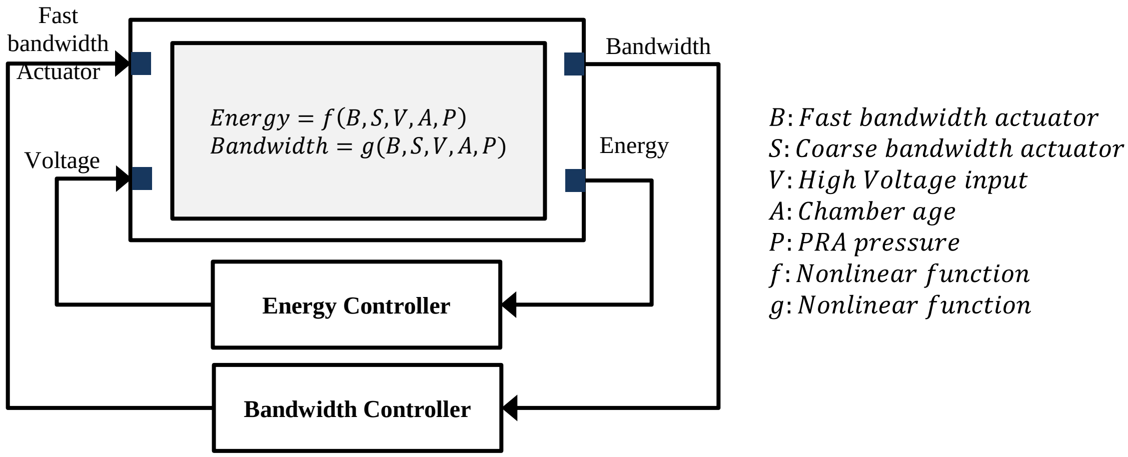

Figure 3 Block diagram showing inputs and outputs of the laser system and the full coupling of the outputs to the inputs.

Figure 4 shows the nature of the coupling. Each curve in the figure is a partial function showing a slice of the six-dimensional space created by various quantities. There are two sets of function, one for energy and one for bandwidth. These functions are known only qualitatively at the time of optimization and vary across different modules. This makes solving for an optimum point challenging.

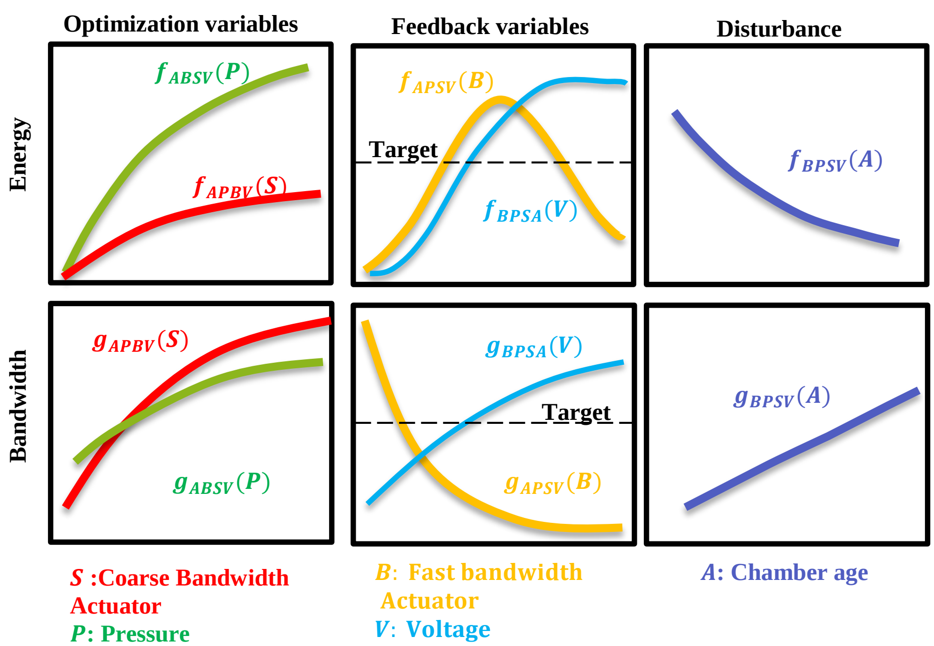

Figure 4 2-dimensional sections of a 6 dimensional-space. The heavy coupling makes it nontrivial to find optimum settings for the pressure (P) and the CBA state (S). The functions, $\boldsymbol{f_x}(\boldsymbol{y_1}, \boldsymbol{y_2}, \ldots)$ and $\boldsymbol{g_x}(\boldsymbol{y_1}, \boldsymbol{y_2}, \ldots)$ are partial functions of their argument, $\boldsymbol{y_1}, \boldsymbol{y_2}, \ldots$ when $\boldsymbol{x}$ is a constant.

Pressure	Coarse Bandwidth Actuator	Remarks	Energy Margin	Bandwidth margin
High	High	Laser efficiency will be high Voltage required for nominal energy will be low. MO energy will be too low – constraint not met Bandwidth will be too high – fast actuator will saturate	High	Low
High	Low	Bandwidth can be too low at nominal fast bandwidth actuator position	Moderate	Low
Low	High	Bandwidth will be too high – fast actuator will saturate Low pressure causes bandwidth range to be small – fast actuator will saturate under moderate level of disturbance Low pressure and saturated bandwidth actuator lead to poor laser efficiency requiring high voltage and thereby reducing energy control margin	Moderate	Low
Low	Low	Laser efficiency will be too low Bandwidth will be too low that can cause actuator saturation further contributing to low laser efficiency	Low	Low

Table 1 Effect of extreme settings on energy and bandwidth margin

Table 1 describes why extreme values of pressure or the CBA lead to undesirable performance in terms of the control margin available. Interestingly, bandwidth margin is low for all cases indicating that the optimum must lie somewhere in between extreme settings of pressure and the CBA. In general optimal pressure and bandwidth settings follow an inverse relation.

2. AGO ALGORITHM

2.1 Closing the Loops

The automated gas optimization algorithm strikes the balance between energy and bandwidth margins by closing feedback loops around them. Energy feedback loop monitors energy and adjusts voltage to maintain constant energy. Therefore anything that affects the laser efficiency is reflected in the corresponding feedback control voltage. Thereby the margin on energy is approximated by the margin on the control. The range of voltage input is limited and therefore a sub-range within the absolute limits can be designated to indicated acceptable margin on energy control and hence laser's efficiency.

Bandwidth loop uses the CBA to regulate bandwidth. To ensure sufficient margin on bandwidth control, the fast bandwidth actuator (FBA) is positioned near the center of its range. This is not trivial because the bandwidth range is unknown and changes with pressure and CBA. To overcome that, an estimator is employed that exploits the fact that energy and bandwidth curves are covariant with the FBA. The estimator determines the slope of energy vs FBA in real time, and the FBA is locked on to a target slope value that corresponds to the middle of the FBA’s range.

2.2 Automated Algorithm

With the energy and bandwidth loops closed, all that remains is adjusting the pressure loop until a stopping condition is reached. These conditions are achieved when all the constraints are met. The two main constraints are on the feedback voltage and the MO energy at nominal system energy output. The range for voltage and MO energy is selected based on the average performance of multiple XLR lasers. Since the pressure changes can only be negative, the pressure is first set to maximum followed by successive discrete "bleeds" where the pressure drops. After every drop, the laser is pulsed and the CBA is adjusted until desired bandwidth is reached. The entire procedure is followed until both stopping conditions are met or an abort condition is met. The abort conditions include voltage going outside the stopping condition or pressure reaches a lower limit.

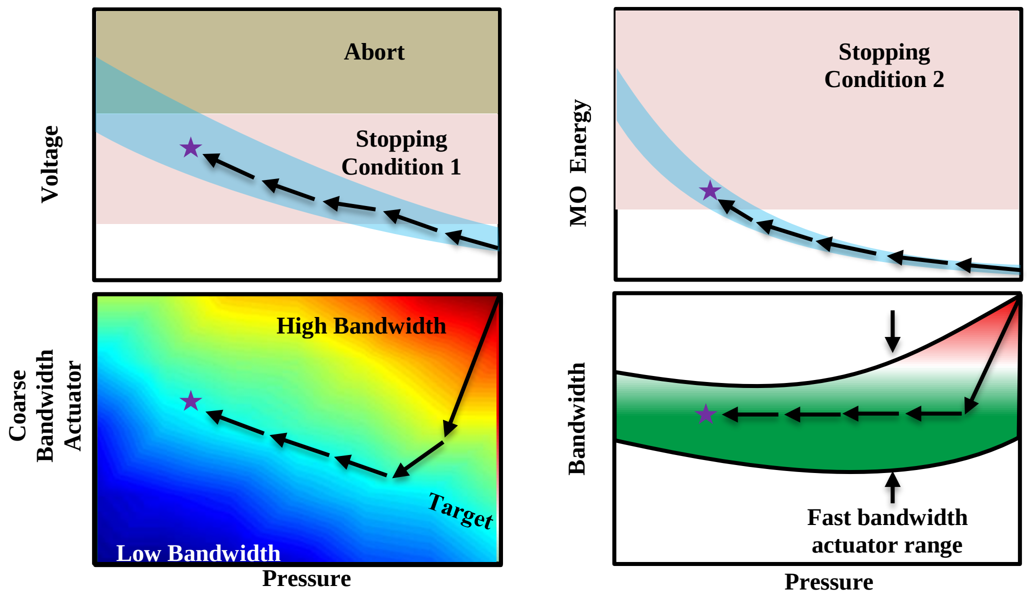

Figure 5 Illustration of the optimization procedure. The arrows show the direction in which the indicated quantities move when a discrete adjustment is made to pressure and the CBA. Energy is maintained by the voltage and bandwidth is maintained by the CBA. Optimization stops when both voltage and MO energy are in the shaded stopping condition zones. The end of optimization is indicated by the star. Blue shaded regions in the top plots indicate total variation in voltage and MO energy expected due to pressure and CBA.

3. AGO PERFORMANCE

The performance of AGO is characterized against its goals that include repeatability and ability to perform the optimization similar to a manual procedure in the allotted time frame. The laser behavior is a slowly varying function of the number of pulses fired; therefore the optimal trajectory of pressure and CBA should follow a smooth curve as a function of number of pulses. Performance is also judged based on the margin achieved at the end without breaking constraints on voltage and MO energy. Figure 6 shows an example from a field laser offering comparative data on laser performance with manual and automated optimizations. Large sudden drop in the voltage is indicative of a new chamber installation. The figure shows two chamber lives with intermittent manual optimizations and one chamber life with AGO performed on every refill (indicated by jumps in the pressure). Optimal pressure trajectory over the life of chamber will typically follow a shallow 'U'-curve and the voltage should show steady rise while MO energy stays constant. This behavior is readily seen with the AGO data. Manual procedure also achieves the same but with more fluctuations.

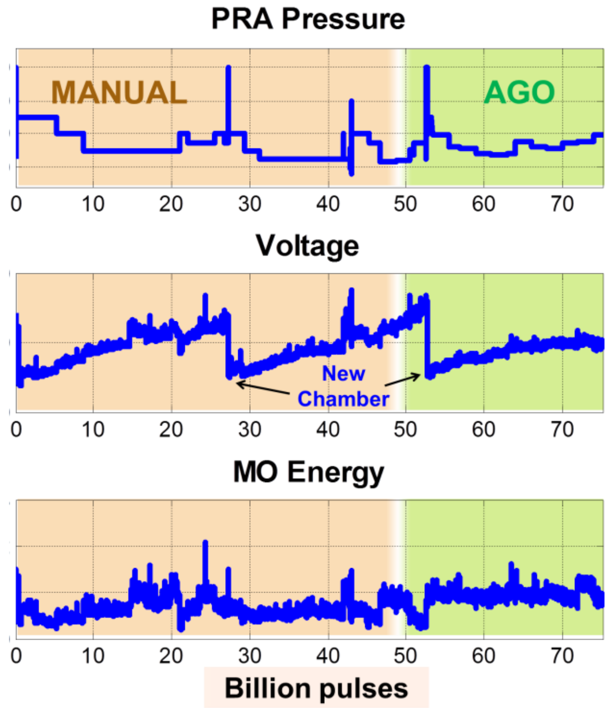

Figure 6 Manual versus automated gas optimization. AGO allows laser performance to be similar to that obtained with manual optimization as desired.

4. FUTURE WORK AND CONCLUSIONS

AGO has been deployed to several systems in the field and has been a great success in achieving its goals. The objective of mimicking the manual optimization procedure and replacing it with an automated feature is achieved with further advantages. It allows for reduced laser downtime, fewer incidences of field service engineer involvement and reduced issues with scanner tool scheduling. AGO is able to perform optimization on every refill without reducing the overall availability. This is important around the end of chamber life because of fast changing behavior. Frequent optimization prevents chances of deterioration of performance across several refills. Furthermore, every AGO is featured with logging that provides data on laser performance that can be trended over the life of a chamber, which can be used to assess laser health, and further improve laser performance. Despite these advances, there remains room for improvement and customizations. The optimization can be formalized by measuring parameters of interest in real-time and optimizing toward a formal cost function. The total time can be further reduced by setting initial conditions near an estimate of the optimal point. AGO can accommodate more laser-specific calibrations that are otherwise done manually. AGO can be made smarter to highlight potential health issues with the laser.

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